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Gallium based Liquid Metal Substrate Integrated Waveguide Switches

Shaker Alkaraki, James Kelly, Alejandro L. Borja, Raj Mitra, and Yi Wang

Abstract— This paper presents a new approach for reconfiguring substrate integrated waveguide (SIW) devices. It involves allowing or prohibiting the wave propagation by using a removable wall which is built from a series of drill holes. When the wall is required the holes are filled with Gallium based liquid metal (LM), thus forming vias. When the wall is no longer required the holes are emptied of liquid metal. The method has been applied to a single-pole single throw (SPST) SIW switch as well as a single-pole double throw (SPDT) switch. Both switches perform well over a wide frequency bandwidth, approaching one octave. The SPST switch performs well from 2.4 GHz to 4.3 GHz. In the on-state (i.e. wall removed) the insertion loss (IL) is ≤ 0.5 dB. In the off-state (i.e. wall inserted) the isolation, is 30 dB. The SPDT switch operates effectively from 4.7 GHz to 7.2 GHz. The IL, between two connected ports, is 0.7 dB. The isolation between unconnected ports is 40 dB. The proposed approach will be applicable within a wide range of different reconfigurable microwave devices.

Index Terms— liquid metal, EGaIn, reconfigurable devices, RF/microwave switch, microwave switches, SIW.

I. INTRODUCTION

CONVENTIONAL air-filled rectangular waveguide (WG) has a range of attractive properties, including: low insertion loss, total confinement of energy and high power handling capability. Unfortunately, conventional waveguide is bulky and sometimes inconvenient to fabricate. Substrate integrated waveguide (SIW) technology provides many of the same benefits as WG and can be used to produce compact, low cost devices using standard printed circuit board manufacturing techniques.

Several designs for reconfigurable devices, based on SIW, have been proposed in the literature. Most relate to antennas and filters. Additionally, there are a smaller number of designs for other devices, including: dividers, couplers, phase shifters, and switches. In approximately half of those papers the device is reconfigured by: 1) adding or removing a via connection using a semiconductor switch [1], 2) by reactively loading the vias using a varactor [2-3], or 3) by adding/removing posts made from solid metal [4]. Furthermore, several designs for single-pole single-throw (SPST), and single-pole double throw (SPDT) SIW switches have been reported. These designs are reconfigured by using pin diodes [5-8], ferrite-loaded materials [9-10], and mechanical methods [11]. There are a handful of papers on SIW structures that can be reconfigured by using Gallium-based liquid metal. The vast majority of these relate to

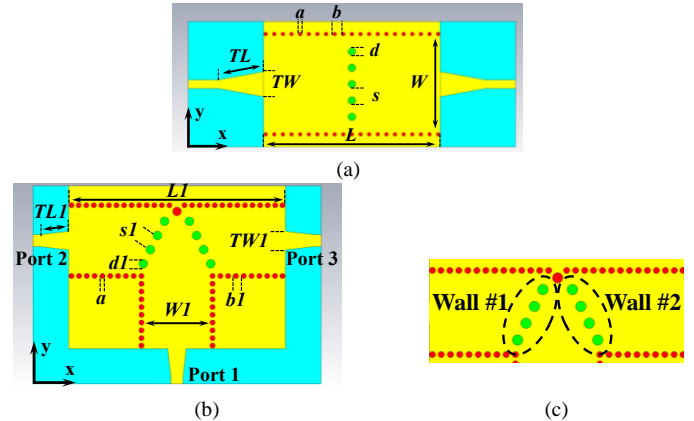


Fig. 1. Proposed switches. (a) SPST. (b) SPDT, (c) inset view of liquid metal walls. Key: substrate = blue, copper = yellow, plated vias = red, liquid metal vias = green.

filter designs. Reconfiguration is typically achieved using drill holes that can be filled or emptied with liquid metal [12-15]. In those papers the vias are used to: 1) control the topology of the filter [12], 2) introduce reactive loading [13], [15], or 2) alter the supported eigenmodes [14]. In [15] the via holes are partially filled with liquid metal. The operating frequency is tuned by altering the depth to which the holes are filled. The geometry of the design in [16] is almost identical to that of the switches, presented herein. However, the concept is very different since the wall in [16] is used for frequency selective filtering rather than blocking. There are a small handful of papers on WG devices that can be reconfigured by using liquid metal. The majority of those papers present designs for switches [17-18].

Currently, the most popular technique for reconfiguring circuits is to use semiconductor switches/tuning elements and this technology is quite mature. However, it suffers from important limitations including: (i) significant overall power consumption; (ii) poor harmonic performance; (iii) limited bandwidth and tuning range; (iv) spurious effects due to isolated areas of metallization; and (v) poor power handling capability. Around 2014, interest started to grow in liquid metals based on alloys of Gallium which can potentially address all of these issues. In this paper we use liquid metal vias, for the first time, to produce a blocking wall within an SIW structure. To demonstrate the practical applications of the approach we present a pair of switch designs. The proposed switches have been validated numerically and experimentally. The performance is competitive with that of other switching

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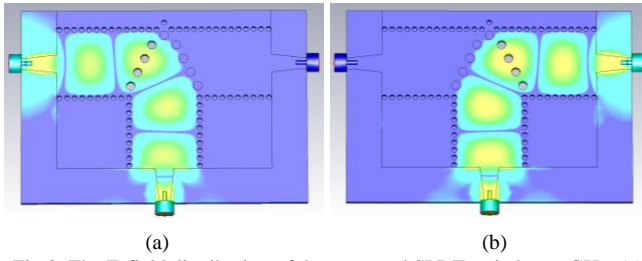


Fig.2. The E-field distribution of the proposed SPDT switch at 6 GHz. (a) state A, and (b) state B.

technologies, in terms of: bandwidth, insertion loss (IL), and isolation. The performance is also temporally stable. Relative to competing devices, the proposed switches are expected to offer significantly improved linearity [19]. In spite of slower reconfiguration time, (expected in seconds to milli-seconds [20-21]), the proposed switches are suitable for applications where high power handling capability and low loss is a priority. The new approach will broaden the horizon for microwave, mm-wave and RF engineers to realize various reconfigurable SIW-based devices such as: filters, power dividers/combiners, diplexers, multiplexers, and couplers.

TABLE I

DIMENSIONS OF THE PROPOSED SPST AND SPDT SWITCH (UNIT: MM).

$TL = 18.3$	$W = 38.5$	$a = 1.5$	$b = 3.43$	$s1 = 4.47$
$TW = 10$	$L = 70$	$d = 3$	$s = 6.6$	$d1 = 2.5$
$L1 = 61.1$	$TL1 = 8.05$	$TW1 = 5.25$	$s1 = 4.47$	$b1 = 2.13$
$W1 = 20$	$a = 1.5$			

II. CONCEPT AND STRUCTURE OF THE DEVICES

The operating state of each switch can be reconfigured by using a series of drill holes that can be filled with, or emptied of, liquid metal. When the holes are filled, they become vias which form a blocking wall within the E-plane of the waveguide. The wall prevents the passage of a travelling wave through the waveguide. For both switches the substrate material is Rogers RO 4003C with a thickness of 1.524 mm, a dielectric constant of 3.55, and a loss tangent of 0.009. The SIW transmission lines were designed using the methodology described in [22]. Table I gives the dimensions of the proposed switches. The width of the SIW (W) controls the lower and upper cutoff frequencies (F_c) of the SIW (i.e. those associated with the TE₁₀ and TE₂₀ modes). For a hollow waveguide having a width (a_h) and a height (b_h), F_c is determined using Eq. (1) and Eq. (2) [23] and the equivalent width of the SIW is determined using Eq. (3) [22].

$$F_{C,mn} = c \sqrt{\left(\frac{m}{2a_h}\right)^2 + \left(\frac{n}{2b_h}\right)^2} \quad (1)$$

$$F_{C,m0} = \frac{mc}{2a_h} \quad (2) \quad \text{and} \quad W = \frac{ah}{\sqrt{\epsilon_r}} \quad (3)$$

where: m , and n are integers and c is the speed of light.

A transition from SIW to microstrip was then designed using the process given in [24]. The length (TL) and width (TW) of the tapered transition were optimized numerically in order to obtain 15 dB of return loss over the majority of the operating frequency band. We also studied the geometrical parameters of a via wall required to deliver a certain level of isolation between a pair of ports. This was achieved by performing a parametric study in CST, which revealed that the isolation is controlled by the ratio of the distance between the liquid metal vias (S) to the via diameter (d), as one might expect. The study reveals that the isolation is: 1) better than 30 dB, when $s/d \leq 2.5$, 2) better than

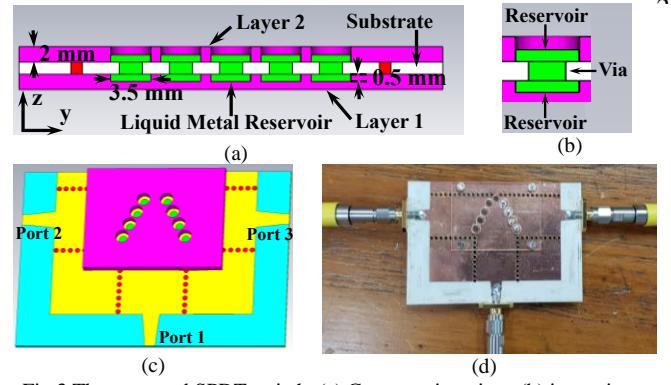


Fig.3 The proposed SPDT switch. (a) Cross section view, (b) inset view of the liquid metal via, (c) top view and (d) fabricated prototype.

40 dB, when $s/d \leq 2$, and 3) better than 50 dB when $s/d \leq 1.5$. Table I gives the dimensions of the proposed switches.

A. SIW SPST Switch

Fig. 1(a) shows the proposed SPST switch. The switch was designed to operate from 2.4 GHz to 4.3 GHz. The E-plane wall is formed from a row of 5 drill holes which are located in the middle of the structure. These drill holes can be filled with liquid metal. Note that all of the holes are filled or emptied at once. When all 5 holes are emptied of liquid metal, the switch is ON. The absence of the wall allows the passage of a travelling wave from ports-1 to -2. When all 5 drill holes are filled with liquid metal, the switch is OFF. The presence of the wall blocks the passage of a travelling wave from ports-1 to -2.

B. SIW SPDT Switch

Fig. 1(b) shows the SPDT switch. Port-1 is connected to the pole of the switch. A signal injected into port-1 can either be routed to ports-2 or -3, depending on the operating state of the switch. Two rows of holes were machined into the device. The four holes within each row are shaded in green in Fig. 1(b) and labelled wall #1 and #2 as shown in Fig.1(c). When liquid metal is injected into all of the holes associated with a particular wall, it is turned ON. When liquid metal is withdrawn from all of the holes associated with that particular wall, the wall is turned OFF. In state A wall #1 is OFF and wall #2 is turned ON. This leads to a connection between ports 1 and 2. The situation is reversed in state B. Fig. 2 shows the simulated electric-field distribution, within the SPST switch, at a particular phase instance. The figure confirms that, when a particular wall is ON, it blocks the passage of travelling waves effectively. The SPDT switch operates from 4.6 GHz to 7.3 GHz. The operating frequency band was set higher than that of the SPST switch, to validate the proposed approach at higher frequencies. Fig. 3 shows a fabricated hardware prototype.

III. ACTUAL FABRICATION CONSIDERATION

This section of the paper discusses the fabrication and actuation of the hardware prototype. The channel structure, used to contain and guide the liquid metal, consists of three layers of clear perspex. Fig. 3(a) shows layers #1 and #2, which incorporate 8 cylindrical reservoirs. Gallium based liquid metal is used because it is the only non-toxic, highly electrically conductive metal that is liquid at room temperature. Gallium based liquid metals have proven to be practical for circuit and antenna applications. From the periodic table we see that four metals are liquid at room temperature (or close to room

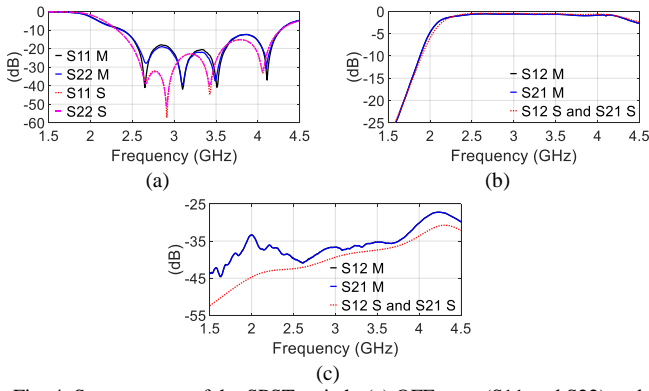


Fig. 4. S-parameters of the SPST switch. (a) OFF state (S_{11} and S_{22}) and (b) OFF state (S_{21} and S_{12}) and (c) ON state (S_{21} and S_{12}). ('M' in the caption stands for measured and 'S' for simulated)

temperature), namely: Mercury, Gallium, Caesium and Rubidium. However, Mercury is toxic and has lower conductivity than Gallium. While, Caesium and Rubidium react explosively with water and oxygen, respectively [25].

A syringe was used to inject or remove liquid metal from each via. This actuation approach is commonly used in the literature [26-27]. Alternative methods of actuation have been reported in the literature, including electrochemically controlled capillary action [28-29] and the use of a micropump [30-31]. One of these existing techniques could be employed in this application. However, liquid metal actuation is not the main focus of the paper. Moreover, altering the method of actuation would have minimal effect on the RF performance of the proposed switches because the actuation circuits would be located beneath the ground plane where the electric and magnetic field strength is minimal. In our experiments, no residues of liquid metal were observed inside the vias after the liquid metal was removed. We actuated the proposed switches several times in order to test their repeatability. The performance was observed to be largely unchanged by the passage of time. We typically reused the same batch of liquid metal in our experiments. Once again, this was found to have negligible effect on the switch performance.

IV. RESULTS AND DISCUSSION

The performance of the proposed switches was simulated using CST Microwave Studio 2019. LM was modelled as a lossy metal having a conductivity of 3.4×10^6 S/m [27]. This is a relatively high value of conductivity; just 17 times lower than that of copper. For this reason, the simulated performance of a device incorporating an RF blocking wall formed from LM vias is virtually identical to that of a device incorporating an RF blocking wall formed from copper vias. Also, the following factors have no effect on the performance of the switches: 1) the dimensions of the reservoirs, and 2) dielectric characteristics of the material used to form the reservoirs. The reason for this is the nature of the switch being an SIW structure, where there is negligible leakage of field through the empty drill holes which are used to form the liquid metal vias. Fig. 4 shows the S-parameters for the SPST switch. When the wall is OFF, the SPST switch exhibits a measured -10 dB S_{11} bandwidth of 1.9 GHz (2.4-4.3 GHz). The insertion loss, over this frequency range, is ~ 0.5 dB. When the wall is ON, the S_{11} and S_{22} are ~ -0.5 dB. The isolation, throughout the operating band, is >30 dB, see Fig. 4(c). Fig. 5 shows the S-parameters for the SPDT switch. The switch exhibits a -10 dB S_{11} bandwidth of 2.5 GHz (4.7-7.2 GHz). In state A, both S_{12} and S_{21} are ~ -0.6 dB (see Fig. 5(b))

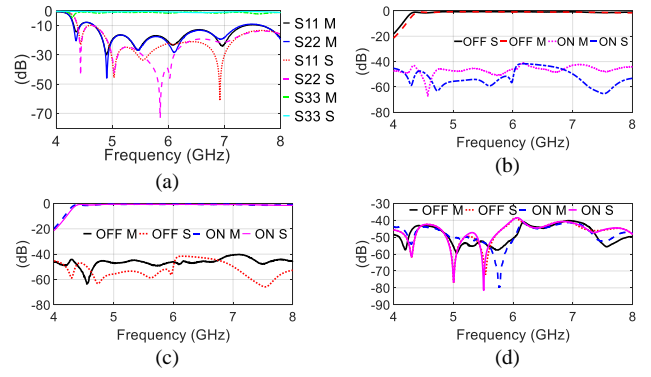


Fig. 5. S-parameters of the SPDT switch in operating state A. (a) reflection coefficients, (b) transmission coefficients (S_{21}), (c) isolation between port-1 and port-3 and (d) isolation between port-2 and -3. (M in the caption stands for measured and S for simulated)

and the isolation between ports-1 and -3, as well as between ports-2 and -3, is >40 dB (see Fig. 5(c-d)). Similarly, for state B, both S_{13} and S_{31} are ~ -0.7 dB with an isolation >40 dB. The switch IL is mainly attributable to mismatch and dissipation in the dielectric substrate. Table II compares the performance of the proposed switches and that of other available switches. The proposed switches have, lower IL and better isolation, over a significantly wider impedance bandwidth than switches reported in the academic literature. The proposed SPST switch also exhibits lower IL than the best of the available commercial-off-the-shelf (COTS) devices. The proposed switches are expected to yield linearity comparable with that of hardwired switches and thus significantly improved linearity compared with switches based on semiconductors [19]. In a system this would lead to improved signal-to-noise ratio and hence data throughput. However, the switching speed, of the proposed devices, is expected to be lower than that of competing devices.

TABLE II
COMPARISON BETWEEN THE PROPOSED SWITCHES AND OTHER TECHNOLOGIES (LM: LIQUID METAL).

Type	Technology	BW-GHZ (%)	IL (dB) (ON/OFF)
[5] SPST	PIN diode/SIW	3-3.6 (18)	3.5/50
[6] SPDT	PIN diode/SIW	8.2-10.3 (23)	2.55/15
[8] SPST	PIN diode/SIW	22 (20)	1.3/10
[9] SPST	Ferrite/SIW	9.5-10 (5)	1/20
[10] SPST	Ferrite/SIW	9.5-11 (15)	1.6/27
[32] SPDT	Not known/coaxial	DC-18 (200)	0.15/90
[33] SPST	PIN diode/coaxial	0.1-18 (198)	1.1/45
LM -SPST	LM/SIW	2.4-4.3 (57)	0.5/30
LM -SPDT	LM/SIW	4.7-7.2 (42)	0.7/40

V. CONCLUSION

This paper has presented a pair of SIW switches. The switches are reconfigured by using vias that can be filled or emptied of liquid metal. The switches serve to demonstrate a method which can be applied more widely to reconfigure SIW-based devices. The proposed method was validated numerically and experimentally. Both switches were found to exhibit insertion losses (in the ON-state) below 0.6 dB and isolations (in the OFF-state) >30 dB, both of which are desirable.

VI. ACKNOWLEDGEMENT

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